# Gas Exchange

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Gas Exchange - Podcast Version
TeachMePhysiology

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Gas exchange is the process by which oxygen and carbon dioxide move between the **bloodstream and the lungs**. This is the primary function of the respiratory system and ensures a constant supply of oxygen to tissues, whilst removing carbon dioxide to prevent its accumulation.

This article will discuss the **principles of gas exchange**, factors affecting the rate of gas exchange, and relevant clinical conditions.

## Physics of Gas Diffusion

Gas molecules move randomly within a contained space (such as the lungs). The collision of gas molecules with the sides of the container results in pressure. The **ideal gas law** defines the determinants of pressure in a container.

$$P \propto \frac{nT}{V}$$

$$Pressure\ of\ gas\ in\ container \propto \frac{number\ of\ moles\ x\ absolute\ temperature}{volume\ of\ container}$$

**Fig 1**

Ideal gas law to calculate pressure of a gas in a container

Between two contained spaces, whilst maintaining random motion, the overall movement of gases will cause diffusion from an area of **high concentration to low concentration**. The rate of gas diffusion depends mainly on the following factors:

- Concentration gradient: The greater the gradient, the faster the rate
- Surface area for diffusion – the greater the surface area, the faster the rate
- Length of the diffusion pathway – the greater the length of the pathway, the slower the rate

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## Laws Governing Gas Exchange

Several laws govern gas exchange, including Graham's law, Henry's law, and Fick's law. Together, they describe the **rate of diffusion** of carbon dioxide and oxygen across the alveolar membranes and into the capillaries. To apply these laws, we assume that temperature is 37°C and pressure is also fixed (as they roughly are in the alveoli).

## Graham's law

Graham's law describes how **multiple gases** diffuse, such as in the alveolar space which primarily contains oxygen, carbon dioxide and nitrogen.

$$Rate\ of\ diffusion \propto \frac{1}{\sqrt{molar\ mass\ of\ gas}}$$

**Fig 2**

Graham's Law describing how gases diffuse

Therefore, the **smaller the mass** of a gas, the more rapidly it diffuses, allowing them to reach equilibrium faster.

## Fick's Law

Fick's law describe the rate at which gases diffuse **through a medium** such as the alveolar or capillary wall or blood.

$$Rate\ of\ diffusion = \frac{(\Delta P) \times A \times D}{T}$$

$$Rate\ of\ diffusion = \frac{pressure\ gradient \times surface\ area \times diffusion\ coefficient}{thickness\ of\ medium}$$

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**Fig 3**

Fick's Law describing the rate of diffusion of a gas through a medium

In the lungs, whilst oxygen is smaller than carbon dioxide, the difference in solubility (represented by the diffusion coefficient) means that carbon dioxide diffuses **20 times faster** than oxygen. However, the large partial pressure gradient of oxygen compensates for this, creating a **greater diffusion gradient** than carbon dioxide.

In disease states that impair oxygen ventilation, **oxygen exchange is compromised** before carbon dioxide exchange due to the reduction of the pressure gradient.

## Henry's law

Henry's law describes how **gases** diffuse through **liquids**, such as when gases diffuse into the capillary blood. In this case the solubility of the gas becomes important and is defined by Henry's law.

$$C = kP$$

$$\text{Concentration of dissolved gas in liquid} = \text{solubility constant} \; x \; \text{partial pressure of gas above the liquid}$$

**Fig 4**

Henry's Law describing how a gas dissolves into liquids

Therefore, the higher the partial pressure of a gas, the more will be dissolved in the liquid. However, some gases are more soluble than others, as determined by their solubility constant (k).

Carbon dioxide is inherently **more soluble** than oxygen, allowing it to dissolve more rapidly into the blood compared to oxygen, despite a smaller pressure gradient.

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# Diffusion of Oxygen

In the alveoli, the partial pressure of oxygen is lower than the external environment. This is due to the **continuous diffusion** of oxygen across the membrane into the blood and the diluting effect of carbon dioxide entering the alveoli to leave the body.

The partial pressure of oxygen is even lower in the capillaries than the alveoli, resulting in a net diffusion of oxygen into the blood, following Fick's law. Once oxygen diffuses into the plasma, it binds to haemoglobin within red blood cells, forming **oxyhaemoglobin**. Thus, oxyhaemoglobin is used to transport oxygen through the bloodstream to respiring tissues.

At rest, oxygen has around one second to complete diffusion from the alveolus into the pulmonary capillary. During **exercise**, this reduces to half a second as blood velocity increases. Oxygen exchange only takes half a second to complete when a blood cell enters the capillary, meaning that exercise capacity is not normally limited by the rate of gas exchange.

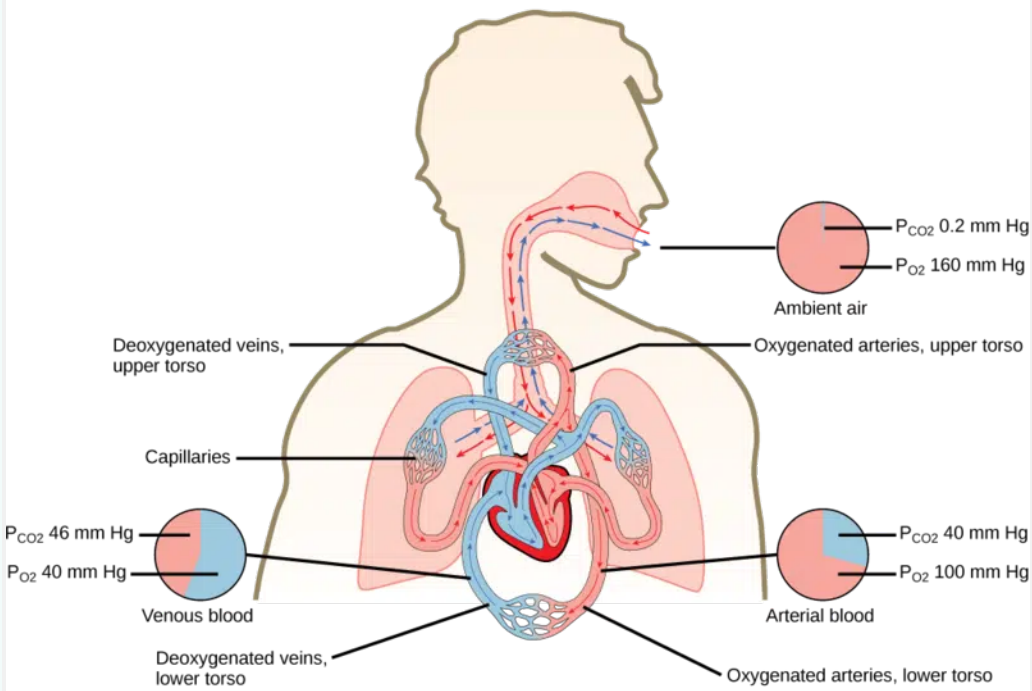


**Fig 5**

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Diagram showing the partial pressures of oxygen and carbon dioxide in the respiratory system

## Diffusion of Carbon Dioxide

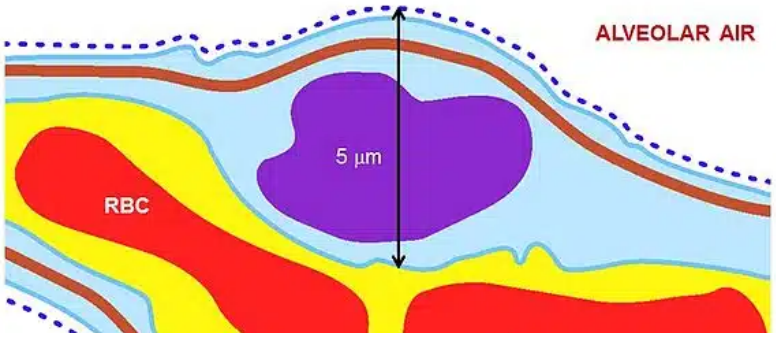
The partial pressure of CO2 is around 45mmHg in the capillary, 40mmHg in the alveoli and 0.2mmHg in the external environment. This **5mmHg capillary-alveolar gradient** drives a net diffusion of CO2 from the capillaries into the alveoli. The CO2 is then exhaled into the external environment.

Carbon dioxide is **transported in the blood** in multiple ways. It can be dissolved, associated with proteins and transported as bicarbonate ions.

## Diffusion Barrier

The **diffusion barrier** in the lungs from the alveoli to the blood cell consists of:

- Alveolar epithelium
- Tissue fluid
- Capillary endothelium
- Plasma
- Red cell membrane

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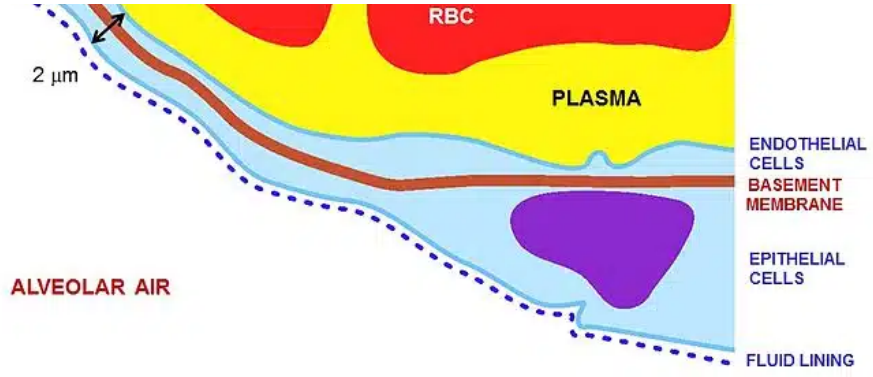


**Fig 6**

Diagram showing the layers making up the diffusion barrier in the lungs

CLINICAL RELEVANCE

## Factors Affecting The Rate of Diffusion

Disease pathophysiology affects the rate of diffusion. Examples include:

- Increased **diffusion distance**
  - Fluid in the interstitial space (pulmonary oedema)
  - Thickening of the alveolar membrane (pulmonary fibrosis)
- Reduced **surface area**
  - Emphysema causes the destruction of the alveolar architecture and the formation of large air-filled spaces known as bullae**.** This reduces the surface area available for gas exchange

CLINICAL RELEVANCE

## Emphysema

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Emphysema is a chronic, progressive disease that results in destruction of the alveoli in the lungs to form larger **bullae**. This greatly reduces the surface area for gas exchange, causing **hypoxia** as oxygen is slower to enter the bloodstream (Type 1 respiratory failure).

The main symptom of emphysema is **shortness of breath;** however, patients may also experience wheezing, a persistent cough or chest tightness.

Emphysema and chronic bronchitis are both encompassed by the term **Chronic Obstructive Pulmonary Disease** (COPD). Whilst smoking is the most common cause of COPD, other risk factors include exposure to second-hand smoke, occupational fumes or dust and high levels of pollution.

Management depends on the **stage of the condition** (i.e. the degree of symptoms and airway obstruction) but typically includes:

- Smoking cessation
- Bronchodilators to reduce bronchial constriction
- Inhaled corticosteroids to reduce airway inflammation
- Antibiotics and oral steroids to treat infectious exacerbations of the disease
- Long-term Oxygen Therapy (LTOT) in severe progressive disease

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**Fig 7**

Emphysematous lungs

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